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Energy production of photovoltaic systems: Fixed, tracking, and concentrating

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ABSTRACT

This work compares the energy production (EP) of four photovoltaic system configurations: fixed, 1-axis and 2-axis tracking flat plate, and concentrating photovoltaics (CPV). The EP comparison is based on real performance data from systems installed in Spain in 2009. These systems are located close to each other but house different configurations. Many of the systems analyzed are new installations in 2008, including two of the largest CPV systems in the world that together have 9.3 MW and represent more than 50% of the world's total CPV. The EP analysis shows: (1) compared with the fixed flat plate systems, 1-axis and 2-axis tracking flat plate systems have 22.3% and 25.2% gain in the annual EP, respectively. These real EP gains are less than 32.1% for 1-axis and 38.7% for 2-axis tracking, which are the predicted gains when only considering the difference of captured illumination by these configurations (based on the data from Photovoltaic Geographical Information System (PVGIS)). (2) The EP from CPV systems is quite close to that from fixed flat plate systems. This differs from the predicted 16.1% gain from CPV when only considering the illumination difference. Besides comparing the energy production, the performance ratio (PR) is also estimated and analyzed for the different configurations, based on the best available irradiation data. PR measures the agreement between the operation of a real system and of an ideal system that only considers the nominal module efficiency loss. The analysis shows the PR decreases in the order: fixed, 1-axis, 2-axis tracking flat plate, CPV.

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Contents

1. Introduction

In 2009, *photovoltaic* (PV) reached the third place following wind and gas in Europe for installed capacity that year. By the end of 2010, there was more than 30 GW of PV installed. Solar electricity is becoming a mainstream energy source [1].

Sun tracking is used in large grid-connected photovoltaic plants to maximize solar radiation collection. With tracking, the gain in energy production (EP) over optimally tilted fully static arrays [2,3] is expected to be up to 40%. Thus, with the deployment of PV, there has been a growth in sun tracking systems of both the 1-axis and 2-axis types [4–6].

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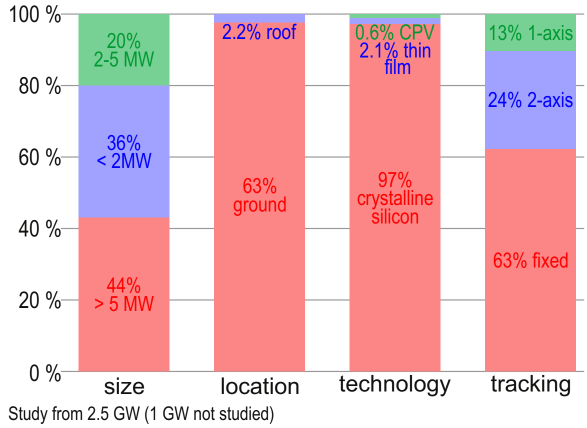

Fig. 1. Characteristics of 2.5 GW of photovoltaic systems installed in *Spain* by 2008.

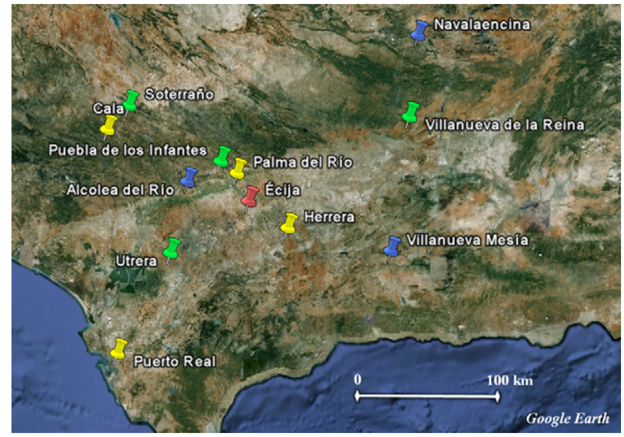

Fig. 2. Locations of the studied installation near Seville.

For almost as long as the commercial flat plate PV has existed, *concentration photovoltaics* (CPV) has been in development. At its inception, it was expected to become the technology that led to the lowest cost of solar electricity [7–9].

Near 20 MW of cumulated CPV power is installed in the world. About 75% of it is installed in Spain [10]. About 10.2 MW (50% of world's total CPV) was installed during 2008 by Guascor Foton, a Spanish company that holds the licensed Amonix technology.

There is very little published work on the EP of different PV configurations that lie near each other [2,6,11]. There are some publications on CPV, few of which describe real CPV EP data [12].

The EP of photovoltaic systems is important because implementation of the feed-in tariff energy policy is directly related to the produced energy in terms of kWh rather than to the installed system capacity in terms of peak power (Wp). Therefore the EP is strongly related to the profitability of the investment.

EP estimates require irradiation data on the PV modules. *Photovoltaic Geographical Information System* (PVGIS) incorporates a solar radiation database and gives climatological data of Europe. PVGIS makes it possible to calculate long-term average values and daily profiles of the irradiation on PV modules [13]. This data has been used to assess and optimize the energy yield from fixed or 2-axis tracking flat plate PV systems [14–18]. PVGIS estimates have been widely used by developers to compare EP between fixed and tracking installations. Thus, we use it here to calculate the theoretical achievable EP for different PV configurations.

ASIF: *Asociación de la Industria Fotovoltaica* (*Solar Photovoltaic Industry Association*; Madrid, Spain) published [19] the following distribution of system types for 2.5 GW of the total 3.5 GW PV installations in *Spain* by 2008. The large number of sampling points and the wide distribution by size, location, technology and system configuration make these installations a rich data set for comparing different system configurations. Fig. 1 shows four different classifications of these PV installations. Of particular interest for this study, more than 1/3 of these installations have sun tracking: 24% of the 2.5 GW have 2-axis tracking and 13% have 1-axis tracking. The rest are fixed systems. 0.6% of the total installations are CPV. These CPV installations include two of the largest in the world [10], with the largest system located in the less sunny north of *Spain*, and the second largest located in the sunnier south. Both are commercial installations, rather than research prototypes used for demonstration purpose.

This work compares the real EP of these fixed, 1-axis, 2-axis, flat plate and CPV installations. The comparisons are made within each system, comparing real with predicted performance, and across systems, comparing real performance. This work also uses the best available irradiation data to estimate the performance ratio (PR), a measure of the agreement between the operation of a real system and of an ideal system that only considers the nominal module efficiency loss.

We note that the CPV systems studied in this paper are all of the high-concentration type and thus need 2-axis sun tracking to gather the *direct normal irradiance* (DNI). Since 2-axis tracking is considered a default configuration for CPV, it is not explicitly addressed in the following discussion. The “2-axis tracking” we do address refers to flat plate installations with 2-axis tracking.

2. Energy production in a high irradiation region: southern Spain

We compare the measured 2009 EP of fixed, 1-axis and 2-axis tracking flat plate, and CPV installations near Seville. Seville is a province in the southern Spain, in the *Andalusian* region, that is an area of high irradiation.

Fig. 2 shows the locations of the studied installations with fixed systems, 1-axis tracking flat plate, 2-axis tracking flat plate, and CPV.

The installations in Fig. 2 are located within a circle of 150 km radius. If we set the *Écija* CPV installation as the center, the fixed systems lie within 140 km of it (average distance 77 km), the 1-axis systems lie within 170 km (average 106 km), and the 2-axis systems lie within 130 km (average 85 km).

Table 1 presents the installations studied and their capacities. All of them adopt crystalline silicon solar cells and some are forming a so-called *solar orchard* or *solar farm*. The EP data of these installations are collected directly from owners or through the *Sonnenertrag* database [20].

Table 1
Locations and capacities of studied installations.

System	Location	Peak power
Fixed	Puerto Real	2.97 kWp
	Palma del Río	13.25 kWp
	Cala	100.00 kWp
	Herrera	136.60 kWp
1-Axis	Navalaencina	5.69 kWp
	Villanueva de Mesía	5.78 kWp
	Alcolea del Río	100.98 kWp
2-Axis	Soterraño	10.64 kWp
	Villanueva de la Reina	93.60 kWp
	Puebla de los Infantes	102.40 kWp
	Utrera	113.40 kWp
CPV	Écija	1.5 MW

Table 2
Ratio of irradiation at weather stations.

Installation	Weather station	Ratio
Puerto Real	Puerto de La Cruz	100.2%
Palma del Río	Palma del Río	100.0%
Cala	El Campillo	99.7%
Herrera	Santaella	98.6%
Navalaencina	Linares	101.1%
Villanueva de Mesía	Loja	101.2%
Alcolea del Río	Villanueva del Río	99.3%
Soterraño	El Campillo	97.9%
Villanueva de la Reina	La Higuera	101.0%
Puebla de los Infantes	Palma del Río	101.4%
Utrera	Los Morales	100.1%
Écija	Écija	100.0%

To calculate the performance ratio later in this paper, we need the real irradiation data on the PV panels. Since this data is not available for the above installation locations, we use data from the nearest weather stations (WS) to predict it. These WS data come from the *Andalusian Energy Agency* database [21]. Table 2 shows the locations of each installation and its nearby WS, and the ratio of the irradiation at the installation location relative to that at the WS (denoted as "Proportion"). The data used to calculate the irradiation ratio comes from PVGIS, and is deliberately chosen to fit the particular installation types; e.g., for the CPV installation, we choose DNI while for the 2-axis flat plate installations, we choose global normal irradiance (GNI).

Since all the values in the "Ratio" column are close to unity, there is trivial difference in irradiation between the WS and the installation locations. Moreover, since these real-time WS data are used to calculate a relative ratio, the discrepancy becomes even more negligible. Our method for using the WS data to predict the real-time irradiation at the PV installations is detailed in the PR analysis in Section 2.3.

2.1. Energy production estimate

Fig. 3 and Table 3 present the EP estimates for different PV configurations if they were to be located at *Écija*. This estimate is based on the irradiation data from PVGIS and a constant PR of 75%. This simple estimate provides reference EP that would be expected by the developers before new installations.

This EP estimate is based on 75% PR, assuming that, besides the nominal module efficiency loss, there is 25% loss that occurs during real operation due to temperature effect, inverter loss, mismatch between components, dirt on panels, system degradation, etc. Since systems of different configurations use the same PR, the EP difference shown in Fig. 3 and Table 3 comes from the difference in

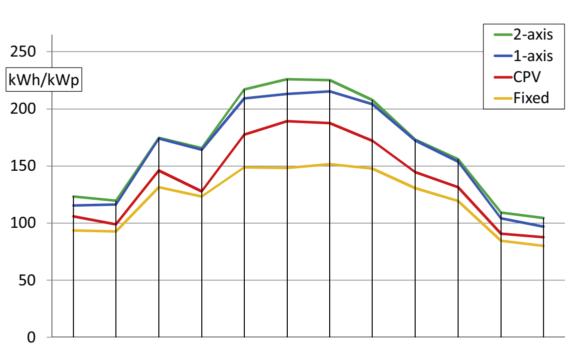

Fig. 3. EP estimates for fixed, 1-axis and 2-axis tracking and CPV systems at *Écija, Seville*.

Table 3
Comparison of annual EP estimates for different PV configurations at *Écija*. The two columns on the right shows the EP ratios of different configurations by setting fixed flat plate PV or CPV as the reference.

System	Energy production	Ratio	Ratio
Fixed	1452 kWh/kWp	100.0%	87.5%
CPV	1659 kWh/kWp	114.3%	100.0%
1-Axis	1939 kWh/kWp	133.5%	116.8%
2-Axis	2001 kWh/kWp	137.9%	120.6%

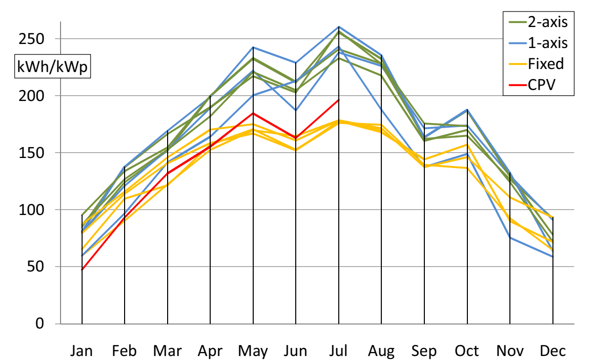

Fig. 4. Real monthly EP for all fixed, 1-axis and 2-axis tracking flat plate and CPV systems in 2009.

captured irradiation. CPV only captures the DNI while all the other three flat plate configurations capture global irradiation at different incidence angles. The difference in EP also results from the rating difference in the capacity of flat PV systems and CPV systems. Flat plate PV is rated at 1000 W/m^2 while CPV is rated at 850 W/m^2.

There are two main types of 1-axis tracking systems: tilted along a north-south oriented axis and tilted along a vertical axis. The EP estimates for both types are very close, thus for simplicity, only the vertical axis is considered in this work.

The data in Table 3 indicates that, CPV, 1-axis and 2-axis tracking flat plate PV are expected to have 14.3%, 33.5%, and 37.9% EP gain, compared with fixed plat plate PV.

2.2. 2009 real energy production

This section first compares the real EP across fixed, 1-axis and 2-axis flat plate throughout 2009. It then compares the real EP between planar and CPV from January to July (the CPV EP is only available during these months).

2.2.1. 2009 energy production of planar systems

Fig. 4 presents the real monthly EP in the 12 installations in 2009. Table 4 shows the average and *sample standard deviation* (S.S.D.) of the real annual EP in 2009 for different flat plate configurations. The S.S.D is given in kWh/kWp and in percentage over the average.

The four fixed and the four 2-axis tracking flat plate installations display very consistent EP data, indicated by the 3.8% and 2.3% *sample standard deviation* from the *average*, respectively. Furthermore, these already small deviations can be partially attributed to the irradiation difference across the installation locations. In Table 5,

Table 4
Annual 2009 EP average and *sample standard deviation* (S.S.D.) for planar installations.

	Fixed	1-Axis	2-Axis
Avg. (kWh/kWp)	1610.2	1936.5	2019.7
S.S.D. (kWh/kWp)	61.0	191.7	46.6
S.S.D. (%)	3.8%	9.9%	2.3%

Table 5
Annual GHI *average* and *S.S.D.* from PVGIS and WS in 2009 for planar installations.

		Fixed	1-Axis	2-Axis
PVGIS GHI	Avg. (kWh/m^2)	1725	1699	1713
	S. Std. Dev. (kWh/m^2)	27.7	3.5	33.4
	S. Std. Dev. %	1.6%	0.2%	2.0%
2009 GHI	Avg. (kWh/m^2)	1807	1777	1810
	S. Std. Dev. (kWh/m^2)	18.0	30.7	33.3
	S. Std. Dev. %	1.0%	1.7%	1.8%

this difference is given as 1.0% and 1.8% irradiation deviation for fixed and 2-axis installations, respectively.

To account for this irradiation difference, we calculate the average global horizontal irradiance (GHI) for the installations of the same configuration shown in Table 5. These data come from both the nearby WS and the PVGIS database. We use these average GHI numbers to correct the EP (as detailed in one of the following paragraphs explaining Table 6) and compare it across different configurations.

Table 6 shows the ratio in EP of tracking systems over fixed installations. The first row has been estimated from the average of irradiation given by PVGIS at installation locations. The second row gives the real gain in EP based on the *Average* EP presented in Table 6.

The third and the fourth rows use the average irradiation data from PVGIS and WS given in Table 5 to correct the EP. Thus they account for the irradiation difference across the three configurations. For instance, simply comparing the 1-axis and fixed EP presented in Table 6 results in a ratio of 120.3%. Multiplying that ratio by a correction factor of 1725/1699 based on the PVGIS irradiation data (see Table 5) gives a new ratio of 122.1%. With this correction we exclude the influence of the irradiation difference and only reflect the performance characteristics of different configurations.

From Table 6, we see the real EP gain of tracking systems over fixed systems is less than what is estimated by simply applying PVGIS data. Comparing the first and the last rows, the real EP gain of 1-axis tracking over fixed is only 69.5% of the estimated gain, and the real EP gain of 2-axis tracking over fixed is only 65.1% of the estimated gain.

2.2.2. January to July 2009 energy production of planar and CPV systems

The CPV power plant we investigate is the 1.5 MW installation located in *Écija*. This installation has the *Amonix Guascor Photon* CPV system. Each CPV system is 50′ tall by 50′ wide and consists of five units, called *MegaModules*, that house Fresnel lenses that concentrate 500 times the sunlight onto solar cells. The installation is constituted by 60 towers, each of which is mounted on a sun tracker and has a nominal power of 25 kWn. This rating of nominal power (Wn) is different from the standard rating of peak power (Wp) that is widely used in flat plate systems, because it considers system losses other than losses from the PV panels. To allow consistent comparison between CPV and other flat plate installation, we adopt the concept of peak power in the following analyses. Each tower in the Écija CPV installation has a peak power of 28.75 kWp.

Table 6
Percent change in EP of tracking over fixed systems.

	Fixed	1-Axis	2-Axis
Estimated ratio	100.0%	132.1%	138.7%
2009 real ratio	100.0%	120.3%	125.4%
2009 ratio corr. by PVGIS	100.0%	122.1%	126.3%
2009 ratio corrected by WS	100.0%	122.3%	125.2%

Table 7
Monthly EP average and S.S.D. for January to July 2009 for *Écija* CPV.

	Avg. kWh/kWp	S.S.D. kWh/kWp	S.S.D. %
January	54.4	5.5	10.2%
February	107.1	6.1	5.9%
March	151.6	5.9	4.2%
April	178.8	5.4	3.0%
May	212.2	5.6	2.6%
June	187.5	6.5	3.5%
July	225.7	13.2	5.8%
Total	1103.6	48.1	4.4%

Table 8
PVGIS and real GHI for fixed, 1-axis, 2-axis and CPV installation locations for January to July 2009.

	Fixed	CPV	1-Axis	2-Axis
PVGIS GHI (kWh/m^2)	1113	1099	1102	1109
	100.0%	98.8%	99.0%	99.7%
2009 GHI (kWh/m^2)	1171	1204	1155	1175
	100.0%	102.8%	98.6%	100.4%

Although the 2009 EP data we have for this CPV only covers January through July, the irradiation in these months ranges from the lowest to the highest levels. Table 7 presents the monthly EP averages and S.S.D.s and Fig. 4 plots these averages.

To compare the EP across the four configurations with correction factors that consider the irradiation difference, we use the average GHIs presented in Table 8 that are based on both PVGIS and WS data (similar to Table 5). Since the comparison pool now contains CPV installations, data from only January to July is included.

Correcting for irradiation difference, Table 9 compares the EP across fixed, 1-axis, 2-axis flat plate and CPV installations from January to July. The content resembles that in Table 6 but the absolute average EP is also included with the relative ratios.

From Table 9, we see the real EP gain of tracking systems over fixed systems is less than what is estimated by simply applying PVGIS data, for January through July. The gain for the 7 months is close to the gain for a whole year (see Table 6) since the irradiation during these months ranges from the lowest to the highest levels. We also see the real EP of CPV systems is close to that of fixed systems while CPV is expected to produce more energy from the estimates by simply applying PVGIS data.

2.3. Performance ratio

Performance ratio (PR) indicates the global effect of the losses over the PV installation due to the temperature, an incomplete utilization of the irradiation and to the failures or inefficiencies of the

Table 9
Estimated and real EP for January to July 2009 for fixed, 1-axis, 2-axis and CPV.

	Fixed	CPV	1-Axis	2-Axis
PVGIS estimated EP (kWh/kWp)	890	1033	1199	1251
	100.0%	116.1%	134.7%	140.6%
2009 real EP (kWh/kWp)	978	971	1209	1247
	100.0%	99.3%	123.6%	127.4%
Corr. PVGIS	100.0%	100.6%	124.8%	127.9%
Corr. WS	100.0%	96.6%	125.3%	127.0%

system components.[1] PR is calculated as indicated in IEC 61724 [22]:

$$PR = \frac{Y_f}{Y_r} = \frac{E_U \cdot G_{I,\mathrm{ref}}}{P_0 \cdot H_I} \quad (1)$$

where:

- Y_f is the final yield, it is a daily portion of energy supplied to the grid per 1 kW of the installed PV array. $Y_f = E_U/P_0$ is in h/d (hours per day), it represents the number of hours per day that the system would need to operate at its PV array's rated power P_0 to generate the same daily energy that was supplied to grid E_U.
- Y_r is the reference yield, it is total daily in-plane irradiation normalized to the PV module's in-plane reference irradiance $G_{I,\mathrm{ref}} \cdot Y_r = H_I/G_{I,\mathrm{ref}}$ is in h/d (hours per day), it represents the number of hours per day which the solar radiation would need to be at reference irradiation levels in order to contribute the same incident energy as it was measured. For flat plate *standard test conditions* (STC) $G_{I,\mathrm{ref}} = 1000\,\mathrm{W/m^2}$. CPV panels are rated at $G_{I,\mathrm{ref}} = 850\,\mathrm{W/m^2} \cdot H_I$ is the number of hours per day that the installation would have had a constant irradiation of $1\,\mathrm{kW/m^2}$.

Thus to compare the system operation characteristic in terms of PR across different PV configurations, we must collect data on the available irradiation. Due to the lack of irradiation measurements at the installation locations, we estimate the available irradiation reaching the panels by using data from PVGIS and nearby WS. There are many WS spread across the country that have GHI measurements. Since this is all that is available for 2009, we use these measurements (see Table 2) to predict 2009 irradiations for the four configurations.

We use CPV to show our computations. The average-year DNI for Écija (DNI_{avg}) and the average-year GHI for the closest WS (GHI_{avg}) are read from the PVGIS database. The 2009 GHI for the WS (GHI_{09}) is read from the WS database. We assume that the increase in DNI from the average year adopted by PVGIS to 2009 is proportional to the GHI increase. Then the 2009 DNI at the CPV installation location (DNI_{09}) is predicted as:

$$DNI_{09} = DNI_{avg} \cdot \frac{GHI_{09}}{GHI_{avg}} \quad (2)$$

This method is also used to predict the available irradiation for the flat plate installations. The DNI_{avg} in the above equation must be replaced with the parameter that is appropriate for the configuration being analyzed; e.g., GNI should be used for 2-axis tracking flat plate installations.

Using the predicted irradiation and the real EP, we calculate PR. Fig. 5 presents the monthly averaged PR for the various PV configurations. For *Écija* CPV installation, PR from only January to July 2009 is presented.

The PRs for fixed and 2-axis tracking systems display a consistent gap during the year. Since monthly irradiation is estimated, uncertainties of this calculation could influence the monthly PR. However, it is not the absolute value but the proportion between the systems that is important here, and those proportions remain very consistent.

1-Axis trackers can have two main configurations: tilted axis and vertical axis. Thus even when the annual EP is similar, monthly distributions are different since the tilted axis configuration has more EP in the summer time but less in the winter time. For the sake of simplicity, we have assumed in our irradiation calculations a vertical 1-axis tracking configuration. Therefore the irradiation could be underestimated in summer and overestimated in winter.

[1] From PR definition in IEC 61724.

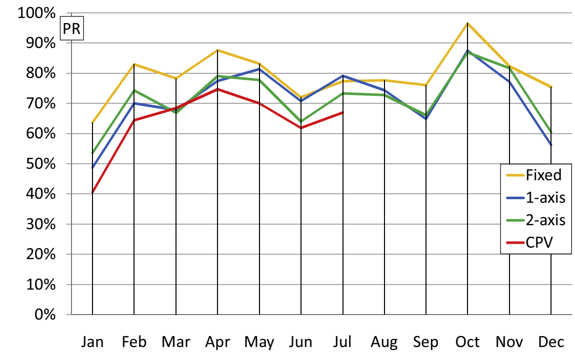

Fig. 5. Average monthly PR for fixed, 1-axis and 2-axis flat plate and CPV installations in 2009.

Table 10
Calculated average annual PRs across flat plate installations in 2009.

	Fixed	1-Axis	2-Axis
Average PR	79.3%	72.4%	71.4%
S.S.D.	3.8%	7.3%	1.7%

Table 11
Calculated average PRs across flat plate and CPV installations for January through July 2009.

	Fixed	1-Axis	2-Axis	*CPV*
January–July PR	78.3%	72.5%	70.5%	65.6%

This would explain why the PR of 1-axis in Fig. 5 is higher than that of fixed and 2-axis in the summer and lower than them in the winter.

Table 10 presents the averaged annual PR and its S.S.D. from average across flat plate installations throughout 2009.

Table 11 presents the averaged PR across the different installation types from January to July 2009.

From the two tables above, we see that PR decreases from fixed to 1-axis tracking flat plate to 2-axis tracking flat plate to CPV.

Fig. 6 plots the monthly PR for different EP values for the four PV configurations from January to July 2009. The regression lines for the four different configurations indicate the same tendency that, higher PR occurs at higher irradiation. Comparing the four regression lines indicates that, fixed flat plate PV has the highest PR among the four configurations.

From the analysis in this section, we see that, one significant reason why the real EP gain of the other three configurations over the fixed flat plate is smaller than the estimated is they all have lower PR.

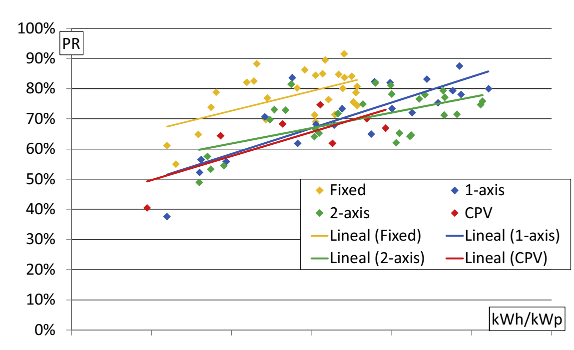

Fig. 6. Monthly PR vs. EP for fixed, 1-axis, 2-axis flat plate and CPV installations for January–July 2009 with regression lines.

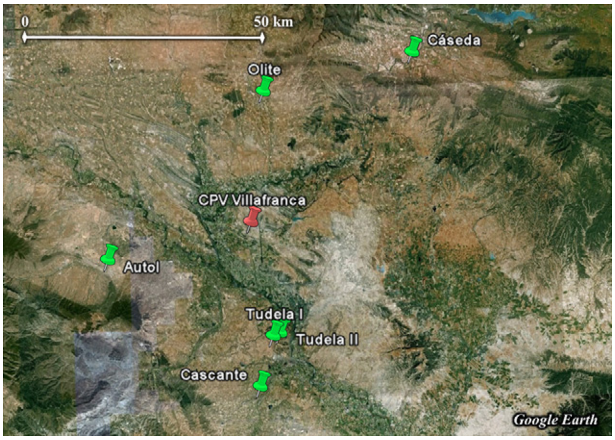

Fig. 7. Locations of installations that are studied in *Navarre*.

3. Energy production in a low irradiation region: northern Spain

We compare the estimated and real EP of CPV and 2-axis tracking flat plate installations in *Navarre* province. Navarre is a province in the northern Spain that is 600 km north of *Seville* and experiences low irradiation. We also estimate and compare the PRs.

This section examines 2009 EP from the world's largest (7.8 MW) CPV power plant that is located at *Villafranca*, in *Navarre* province. This plant houses the same *Amonix Guascor Photon* CPV systems that is installed at *Écija*. It was installed in three phases between 2006 and 2008 [23] and is owned by hundreds of small investors.

Fig. 7 marks the locations of the *Villafranca* CPV installation and that of the six 2-axis flat plate installations. The 2-axis installations lie within a circle of 40 km radius from the CPV installation.

Table 12 lists the locations and the peak power capacities of the 2-axis flat plate installations that are studied in this region. Each is part of a larger installation, but it has its own meter and is independent from the rest of the set. This table also presents the WS located near each installation and the distance to it. WS data is obtained from the *Meteorology and Climatology of Navarre* database [24] and is used to estimate the PR as we did for the southern Spain installations is calculated.

3.1. Energy production estimate

Fig. 8 and Table 13 present the EP estimates for different PV configurations if they were to be located at *Villafranca*. Using the same method as with southern Spain installations, we estimated the EP using PVGIS data. This simple estimate provides reference EP that would be expected by the developers before new installations.

Table 13 indicates that the estimated EP for CPV is only 3.4% greater than that for fixed plate. Moreover, there is no large change in EP when converting from 1-axis to 2-axis installations.

EP estimate in the past were based on the irradiation data from the PVGIS database. The pool of the data is from 1981 to 1990. More

Table 12
Locations and capacities of 2-axis flat plate installations in *Navarre* province and the locations of and distances to their nearby weather stations.

Install.	Power	Weather station	Dist.
Cascante	7.301 kWp	Cascante	2 km
Tudela I	6.300 kWp	Tudela Valdetellas	2 km
Tudela II	34.000 kWp	Tudela Valdetellas	2 km
Olite	11.340 kWp	Olite	2 km
Cáseda	5.940 kWp	Aibar	7 km
Autol	7.480 kWp	Sartaguda	18 km

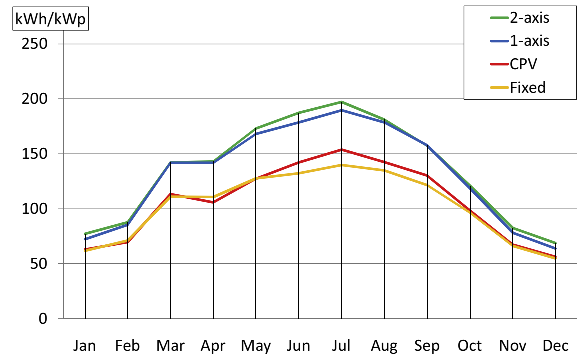

Fig. 8. EP estimates for fixed, 1-axis, 2–axis tracking flat plate, and CPV systems in *Villafranca*.

Table 13
Comparison of annual estimates for different PV configurations at *Villafranca*. The two columns on the right shows the EP ratios of different configurations by setting fixed flat plate PV or CPV as the reference.

	Energy production	Ratio	Ratio
Fixed	1228 kWh/kWp	100.0%	96.7%
CPV	1269 kWh/kWp	103.4%	100.0%
1-Axis	1574 kWh/kWp	128.2%	124.0%
2-Axis	1618 kWh/kWp	131.8%	127.5%

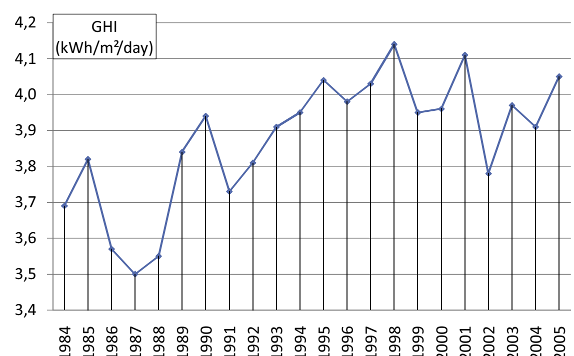

Fig. 9. Average daily GHI for each year from the NASA database for *Villafranca*.

recent data from the NASA database [25] covering 1983–2005 indicates that the 1980s used by PVGIS experienced lower irradiation than the subsequent decades. This is shown in Fig. 9 where the average daily GHI for each year included in the NASA database is plotted. Since PVGIS data comes from the 1980s, it tends to give an underestimate for 2009 irradiation.

PVGIS has been widely used for economic evaluation in PV projects, e.g., to calculate the EP improvement that can be achieved by using sun trackers. Due to this popularity, we present EP estimates based on PVGIS in this work.

Table 14 compares (for the Villafranca CPV) the real 2009 EP with the annual EP estimated from the PVGIS, the NASA databases and by the developer. The DNI estimate using the NASA database is 12.7% larger than the estimate using PVGIS. The developer estimate

Table 14
Annual EP estimates and real EP for *Villafranca* CPV installation in 2009.

	Energy production	Ratio
PVGIS estimate	1269 kWh/kWp	100.0%
NASA estimate	1430 kWh/kWp	112.7%
Developer estimate	2000 kWh/kWp	157.6%
2009 real	1220 kWh/kWp	96.1%

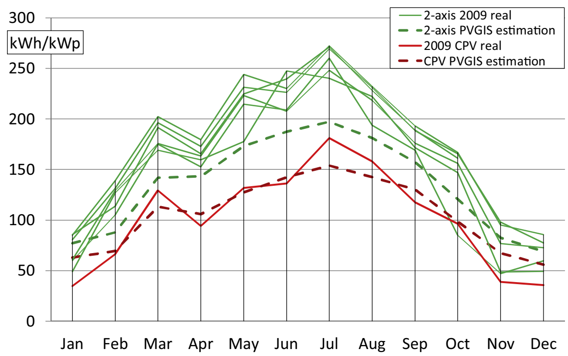

Fig. 10. PVGIS estimates and 2009 real monthly EP for 2-axis flat plate and CPV installations in *Navarre*.

is much larger than the both the other estimates and the real 2009 EP.

3.2. 2009 real energy production

This section compares the real EP of 2-axis flat plate to CPV throughout 2009 in the *Navarre* province.

Fig. 10 indicates the real 2009 EP for 2-axis flat plate and CPV installations with continuous lines. Estimates based on PVGIS data are denoted by dashed lines. We note that there is a 2-axis installation whose EP is abnormally low in May but abnormally high in June. This is because part the EP of May was billed in June, a common occurrence in real operation. However, this abnormality does not affect the annual EP.

Table 15 presents the real 2009 EP and the EP estimate based on PVGIS for six 2-axis flat plate installations. The real EP data was collected from the *Sonnenertrag* database and updated by the owners [20]. This table also gives the S.S.D. and the ratio of the real EP to the estimate.

Table 16 presents the average monthly and annual EP in kWh/kWp for the *Villafranca* CPV installation in 2009. EP values are reported directly by owners in a special database [26] and these EP values come from 23 of the total 313 towers. The table also gives the S.S.D.

Table 17 compares the real 2009 EP and the EP estimate based on PVGIS between the of 2-axis flat plate and CPV

Table 15
Real and estimated annual EP for 2-axis flat plate installations in *Navarre*.

	Avg. EP	S.S.D.	Ratio
PVGIS est.	1649 kWh/kWp	2.0%	100.0%
2009 real	1942 kWh/kWp	7.9%	117.7%

Table 16
2009 monthly EP for CPV at *Villafranca*.

	Average kWh/kWp	S.S.D. kWh/kWp	S.S.D. %
January	34.9	4.0	11.3%
February	66.5	6.5	9.7%
March	129.2	7.6	5.8%
April	94.3	5.7	6.1%
May	131.7	7.4	5.6%
June	136.1	6.4	4.7%
July	181.0	8.1	4.5%
August	158.1	6.9	4.4%
September	117.7	6.1	5.2%
October	96.4	7.1	7.3%
November	38.8	2.4	6.2%
December	35.8	4.1	11.4%
Annual	1220.4	56.0	4.6%

Table 17
Annual estimated and real EP for CPV and 2-axis flat plate installations in *Navarre*.

	CPV kWh/kWp	2-Axis kWh/kWp	EP gain
PVGIS est.	1269	1618	27.5%
2009 real	1220	1906	56.2%

installations. We note that here, the real 2009 EP for 2-axis flat plate is 1906 kWh/kWp, different from the 1942 kWh/kWp given in Table 15. This is because the average irradiation at the 2-axis flat plate installations is 1.9% higher than that at the CPV installation. To exclude this irradiation difference when comparing the two configurations, we correct the original 1942 kWh/kWp value by multiplying by 1/1.019. The last column shows the EP gain of 2-axis flat plate over CPV.

The analysis in this section indicates that, the real EP difference between the 2-axis flat plate and CPV is much larger than the estimated EP difference by simply considering the PVGIS irradiation data.

3.3. Performance ratio

Following the method described in Section 2.3, we use data from PVGIS and WS to predict the available irradiation for the installations in Navarre. For the 2-axis flat plate systems, the WS located near them are listed in Table 12. For the CPV installations, we use GHI data from six nearby WS that lie within a circle of 8 km radius centered at the CPV installation. These stations are located at: *Barranco*, *Yugo*, *Cadreita*, *Funes*, *Traibuenas and Plano*. WS data are obtained from the *Meteorology and Climatology of Navarre* database [24].

Fig. 11 presents the monthly PR for 2-axis installations in *Navarre* and for the CPV installation at *Villafranca* in 2009. Across

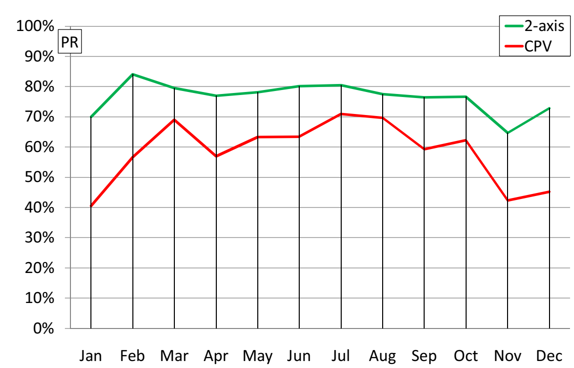

Fig. 11. 2009 monthly predicted PR for 2-axis and CPV installations in *Navarre*.

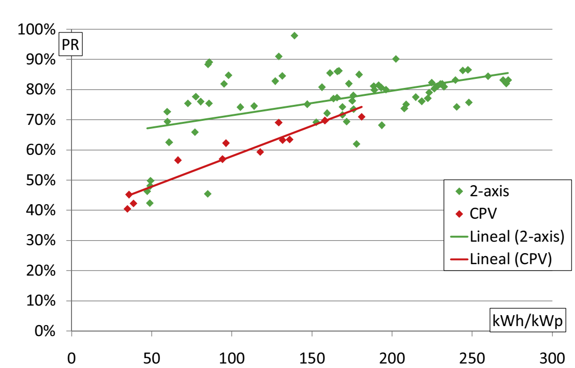

Fig. 12. Monthly *PR* vs. EP for CPV and 2-axis installations in Navarre with regression lines.

the 2-axis installations, the average annual PR is 77.5% with a *S.S.D.* of 5.8%; for the CPV, it is 61.1%.

Fig. 12 plots the monthly PR at different EP for the studied installations. From the analysis in this section, we see that, one significant reason why the real EP gain of 2-axis flat plate over CPV is larger than the estimated is 2-axis flat plate has higher PR.

4. Conclusions

Two quantities that reflect the performance of a PV system are studied in this paper: energy production (EP) and performance ratio (PR). EP in terms of kWh/kWp reflects the ability of a PV system to generate energy. It is affected by: (1) the ability to collect irradiation and (2) the ability to convert irradiation to electricity. On the other hand, PR, a relative ratio, excludes the influence of irradiation capturing ability, and simply reflects how well the captured irradiation can be converted to electricity. This paper presents deep analyses of both parameters across four different PV configurations. Using EP data from real installations and PR estimated from the best available irradiation data, we can make wide comparisons.

Since the three configurations of flat plate systems lie close to each other in southern Spain, the EP of 1-axis and 2-axis sun-tracking installations can be compared to that of fixed systems. The estimate based on PVGIS gives an EP gain of 32.1% and 38.7%, for 1-axis and 2-axis tracking, respectively. However, the real 2009 EP data shows a gain of 22.3% and 25.2%, for these systems, respectively (see Table 6). Moreover, the EP of a nearby CPV (the second largest CPV installation in the world) can be added to this comparison. While the estimate based on PVGIS gives a gain of 16.1% for CPV over fixed flat plate, the real 2009 EP data shows only a 0.6% gain (see Table 9).

The EP difference among various systems is caused by two factors mentioned above: (1) irradiation capturing capability and (2) energy conversion capability. While the former is determined simply by the configuration, the latter can be investigated by examining the PR. We estimate the irradiation reaching the PV panels with the best available data and use it to calculate PR for the various configurations. Our results show that PR decreases from fixed to 1-axis tracking flat plate to 2-axis tracking flat plate to CPV (see Table 11).

In addition to the analysis of the installations in southern Spain, this work also analyzes PV systems in the northern part, including the biggest CPV installation in the world. We compare the EP and PR of this CPV to that of nearby 2-axis flat plate systems. The real 2009 EP of the 2-axis flat plate systems is 56% higher than that of the CPV (see Table 17). The PR value is 77.5% for 2-axis flat plate and 61.1% for CPV (see Table 17).

From the analyses of the actual energy production of PV systems and real-time irradiation from weather stations, we conclude that: simply applying the irradiation data from PVGIS and assuming a constant performance ratio for different PV configurations can lead to overestimation of energy production. The performance ratio must be determined separately for each different PV configuration to enable reliable assessment of the energy production capability.

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